Earth from Sky

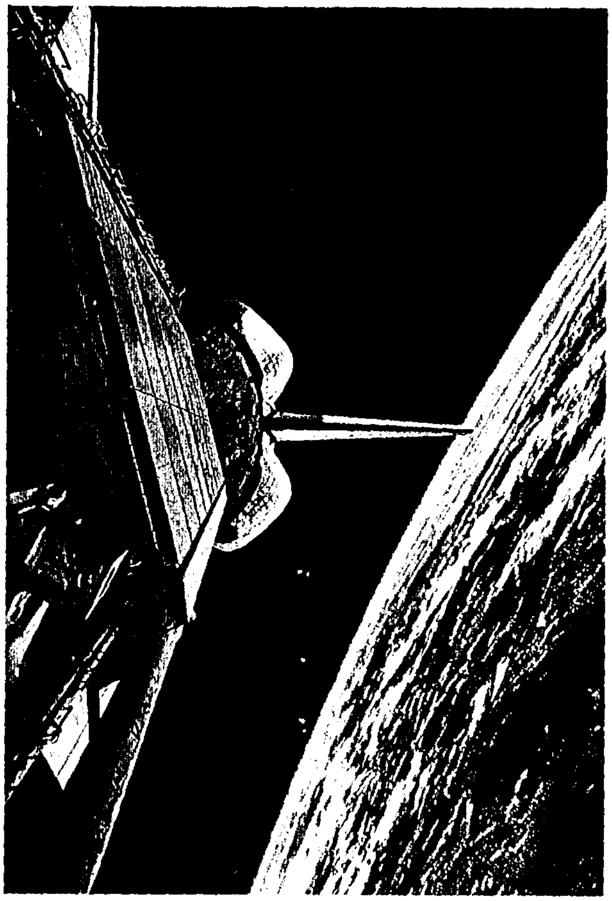
Radar systems carried aloft by the space shuttle Endeavour *provide a new perspective of the earth's environment*

by Diane L. Evans, Ellen R. Stofan, Thomas D. Jones and Linda M. Godwin

Soon after launch on Friday, September 30, the crew of the space shuttle *Endeavour* were treated to a dramatic sight. The Kliuchevskoi volcano in Kamchatka, Russia, was spewing plumes of ash 65,000 feet into the air. After 49 years, the volcano had chosen to erupt that very day. *Endeavour* was carrying a sophisticated radar system designed to study the earth's geology and environment. The equipment had flown only once before, the preceding April. The radar planning team quickly changed the schedule during the next few orbits to capture the fiery peak on film.

Nor was that the only natural event to coincide with *Endeavour's* 12-day flight. On Tuesday, October 4, an earthquake struck near the island of Hokkaido in Japan. Some hours later *Endeavour* was able to scan the coastline for damage from tsunamis.

Radar systems, such as the one on board *Endeavour,* emit radiation of relatively long wavelengths—ranging from a few to tens of centimeters—and record the echo returned by a surface. Comparison of the original and the reflected ray tells researchers the distance, size, orientation, roughness and other characteristics of the reflector. For example, an object tends to reflect that wavelength of radar that matches its own size.



SPACE SHUTTLE *ENDEAVOUR* views the earth with radar. Visible on the shuttle arc flat antenna panels that emit three wavelengths of radar, accompanying electronics (*marked "JPL"*) and an apparatus for measuring atmospheric pollution from satellites (*marked "LaRC"*).

If the surface is oriented so that it reflects the radar right back to the source the way a mirror does, it will look bright. If oriented at some other angle, it will look dark. Features that are rough on the same scale as the wavelength scatter the radiation in all directions, rather than reflecting it back. Thus, plowed fields look bright with shorter-wavelength radar and dark with longer wavelengths, whereas forests look bright at most wavelengths. And whereas a long wavelength can pass right through a hurricane, a short one might divulge details of a storm system's core.

American and European scientists worked together for years to build the radar systems on board *Endeavour.* We used three wavelengths—of three, six and 24 centimeters—called X-band, C-band and L-band, respectively. The two longer wavelengths of radiation were emitted by the Spaceborne Imaging Radar-C (*SIR-C,* pronounced "sirsee") instrument. Scientists at the National Aeronautics and Space Administration's Jet Propulsion Laboratory (JPL) developed this equipment and the data processor in Pasadena, Calif., where the information is retrieved and studied.

The radiation from SIR-C is polarized, so that its electric field vibrates either in the vertical or in the horizontal direction. The reflected rays may be received either vertically or horizontally polarized, giving scientists another means of discrimination. For example, vertical tree branches may reflect one polarization better than the other, allowing investigators to distinguish between different types of vegetation.

The other radar, X-Band Synthetic Aperture Radar (X-SAR, pronounced "exsaar"), operates at three centimeters, emitting and detecting only vertically polarized light. It was developed by the German Aerospace Establishment and the companies of Dornier in Germany with Alenia Spazio in Italy, for the Italian and German space agencies.

On its April and October flights, *Endeavour's* orbit was inclined at 57 degrees to the equator. Drifting slightly on suc-

KLIUCHEVSKOI VOLCANO (*red area*) in Kamchatka, Russia, erupted on September 30. Its last major outbursts had been in 1737 and 1945. The Kamchatka River (*top*) flows across this volatile region where the Pacific plate is sinking under the Eurasian plate. North of the river are dormant volcanoes (*green*); south of it are agricultural settlements (*lines*). Streaks (*yellow-green*) on Kliuchevskoi's slopes indicate new lava flows. For this 18.5- by 37-mile image, the transmitted radiation was polarized horizontally. L-band radiation (24-centimeter wavelength) was received horizontally and vertically polarized, called LHH (*red*) and LHV (*green*), respectively. Also displayed is the vertically polarized component, called CHV (*blue*), of the reflected C-band radiation (six-centimeter wavelength).

DIANE L. EVANS, ELLEN R. STOFAN, THOMAS D. JONES and LINDA M. GODWIN worked on different aspects of *Endeavour*'s April and October flights. Evans, of the Jet Propulsion Laboratory, is the project scientist for the SIR-C radar. She has worked on space-borne radar systems since earning her Ph.D. in geology from the University of Washington in 1981. Evans also conducts research on geologic remote sensing. Stofan is the experimental scientist for SIR-C. She studied the geology of Venus for her Ph.D. at Brown University in 1988 and is also the deputy project scientist on the Magellan mission. Jones flew on both flights of *Endeavour*. A 1977 graduate of the U.S. Air Force Academy, he served in the Air Force for six years. To pursue an interest in planetary science, Jones obtained a Ph.D. from the University of Arizona in 1988. In 1991 he became an astronaut. Godwin, deputy chief of NASA's Astronaut Office, served as a mission specialist on *Endeavour*'s April flight, her second visit to space. A condensed matter physicist who received a Ph.D. from the University of Missouri in 1980, Godwin enjoys flying small planes.

DINOSAUR EXTINCTION, 65 million years ago, may be linked to the Chicxulub crater in the Yucatán, Mexico. The meteoritic impact crater is now buried under 300 to 1,000 meters of limestone, but fracture patterns and water flow reveal the crater's structure. To the left is a mangrove swamp (*yellow and pink band*). The spots (*blue*) indicate tropical forests watered by springs, most abundant near the crater rim, which runs across the center of the image. Data from *Endeavour* may help determine the diameter of the crater (between 110 and 180 miles), a topic of much debate. (L-band total power is red; C-band total is green; and the difference between C- and L-band is blue.)

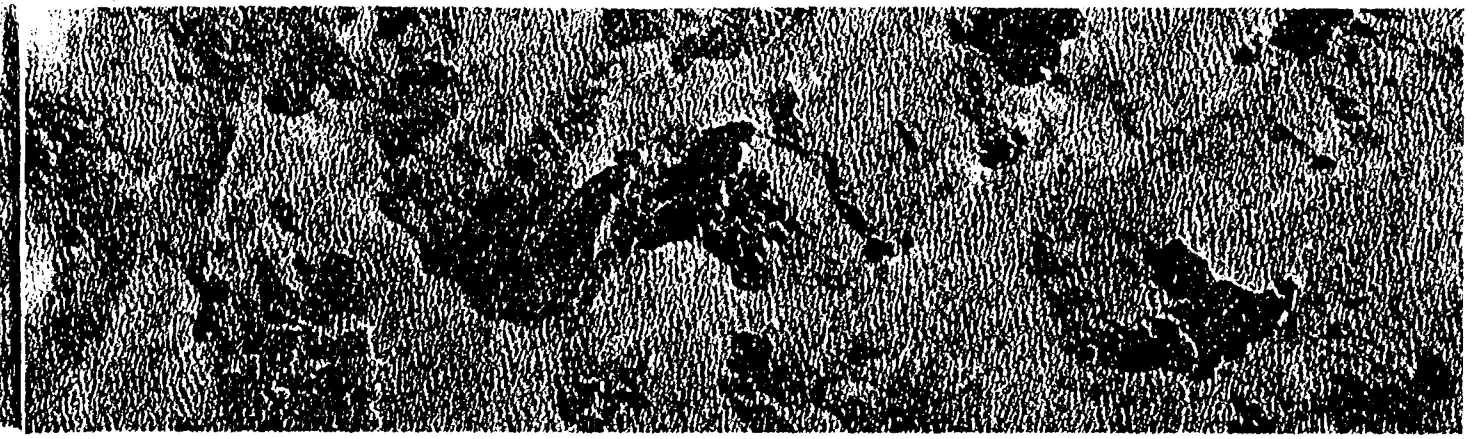
MOUNTAIN GORILLAS that were studied by Dian Fossey live in the bamboo forest (*green crescent*) on the slopes of Mount Karisimbi (14,800 feet). Its neighboring peaks are Sabinyo (12,000 feet) and Muhavura (13,500 feet). These belong to the Virunga volcano chain along the borders of Rwanda, Zaire and Uganda. The volcanoes endanger the town of Goma, Zaire, and nearby Rwandan refugee camps (*white*) on the shores of Lake Kivu (*dark patch at top*). Researchers are using similar images to produce vegetation maps. These maps could be critical to helping the world's last mountain gorillas survive. (35 by 20 miles; LHV red, CHH green, CHV blue.)

***LOST* CITY OF UBAR** in southern Oman was uncovered in 1992 using *LANDSAT*. As in the original data, the city itself is too small to show up in this image by *Endeavour*. But streaks (*pink*) just below the old riverbed, or wadi (*white gash*), reveal buried roads converging on the site. Ubar, one of the enchanted cities of *Thousand and One Arabian Nights*, was a decadent outpost where caravans assembled before ferrying frankincense across the desert. Long believed to be mythical, it probably flourished from about 2800 B.C. to A.D. 300. North of the river are sand dunes (*magenta*); south are bare limestone rocks (*green*). (31 by 62 miles; LHH red, CHH blue, LHV green.)

SILK ROAD may have traversed this corner of the Taklamakan Desert, in China's Xinjiang Province, on its way to Persia, Byzantium and Rome. The image is thought to contain the ruins of Niya, an ancient settlement. The white streak (middle) is the Niya River flowing through ridges and dunes (*blue*). Enhancement (*inset*) reveals a linear feature, probably a man-made canal leading off the river. Such images of deserts and dunes can also help predict sandstorms. (22 by 51 miles; CHH red, LHH green, LHV blue.)

RECLAIMED LAND in Flevoland, the Netherlands, is used for agriculture and forestry. This image from *Endeavour's* April mission shows bare fields (*blue*). Above the canal (*black*) is an old forest (*red*); on the canal's shore is the city of Harderwijk (*white*); and specks in the canal are boats. Such images aid in studies of crops and soil conditions. The pentagon (*lower right corner*) is a reflector for calibrating the radar. (15.5 by 15 miles; L-band total red, C-band total green, X-band vertically polarized and received blue.)

AMAZON FLOODS (*yellow and red*), imaged in April, have since receded. The Rio Negro (*top, blue*) and Rio Solimões (*bottom*) meet a few miles downriver to form the Amazon. A road (*center, thin line*) can be seen connecting a cleared patch (*blue*) in the forest (*green*) to a tributary of the Rio Negro. Researchers use radar to measure the extent of flooding or clear-cutting and the biomass of forests. They can then deduce the carbon dioxide intake, essential to studies of global warming. (5 by 25 miles; LHH red, LHV green, LVV blue.)



ICE FLOES (*brown and white)* ride cm swells in the Weddell Sea, Antarctica, **creating [his rippled image.** Stretches of **open** water (*blue*) **barbor areas w'here** new **ice is forming** (*black wisps).* Sea ice hinders heat flow from the warm ocean to the cold atmosphere, affecting the global climatic system. Radar reveals not only the ice thickness hot also the energy and interactions of the waves. It is especially useful in polar regions, **which have long** periods **of darkness and** extensive cloud cover. (62 **by** 1 8.5 miles; LHV **reel,** LHH green, CHH **blue.**)

LEVEE BREAKS during **the** Midwestern floods of 1993 deposited **several** meters **of** sand (*blue*) **cm farmlands** along **the** Missouri **River mar** Glasgow, Miss. These **farms may now** become **a** muddy-bottom **refuge. Some breaks are visible just below** the **sharp bend ([q>** *center*). Gullies (*yellow*) from the floods **crisscross** the terrain. *Endeavour* **was able** to monitor **the** April **floods of 1994** even as they ravaged parts **of** Illinois. Radar **can also measure the** wetness **of soil or snow** (such **as in California's Sierra** Nevada) **and help** manage water **resources.** (23 by 16 miles; LHH red, LHV green, **inverse of** LHH + LHV **bloc.**)

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cessive ***passes-*** each orbit took 90 minutes- it eventually imaged **12** percent of the globe. The radar was focused on several hundred sites selected by the 52 scientific teams.

The crew also tested a new technique for making accurate topographic maps. The radiation is emitted in phase (as for a laser). The phase of the returned wave is detected by two separate antennae or by two slightly displaced passes of the shuttle. The difference in phases recorded in the two instances depends on the distance of the feature being imaged. Such interferometry has revealed changes as small as centimeters in the Topography of California ant] Hawaii between the **April** and October flights.

The bulk of the data was not turned over to JPL until the shuttle landed. But the crew transmitted some images directly to researchers on the ground, along with comments on what they were seeing. This verbal record, together with more than 20,000 frames of film that the astronauts exposed- a record for shuttle missions- is invaluable for interpreting the data. Covering much broader areas than the radar swath, it l)rol'ides context. It has already helped explain anomalies such as shadowy regions in X- ant] C-band images taken during heavy rain in the **Amazon.**

Endeavour landed at Edwards Air Force Base **in ('California on** October 11, **199-1,** having stayed aloft an extra day to finish **all** its tasks. Its mission showed how the unique perspective of space, combined with the power of radar, can let us explore our planet in a way never before possible. From the images taken, we expect to learn which combination of radar wavelengths and polarizations are optimal for future studies. Launched on board a satellite, such a radar system could become a permanent source of information about the state of the earth's forests, rivers and climate- ant] potential hazards such as earthquakes, volcanoes and floods.

FURTHER READING

THE DISPLACEMENT FIELD OF THE LANDERS EARTHQUAKE MAPPED BY RADAR INTERFEROMETRY. D. Massonnet et al. in *Nature,* Vol. 364, NO. 6433, pages 138- 142; July 8, 1993.

SHUTTLE IMAGING RADAR-C AND **X-SAR** MISSION. **I),** L. Evans et al. in *Eos* (*Transactions of the American Geophysical Union*), Vol. *74,* No. 13, pages 145, 158; March *30,* 1993.

ADDITIONAL IMAGES are available from the World Wide Web at http://spacelink.msfc.nasa.gov or ftp to spacelink.msfc.nasa.gov